Technology Investment Strategy Applied to the Mars Exploration Program

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Wouldn't it be Nice if We Had This Table?

Annual Technology Investment (\$M)	Preferred Technologies	Missions Enabled	MEPAG Measurements Enabled	Comments	Technology Candidates (Different Pathway Mix; Sensitivity Analysis)
25	a	3	XX XX	Insufficient dollars to complete all technologies for mission X, resulting in measurements Y not being done.	XX XX
50	b c d e f	4 7 9	XX XX XX XX	Sensitivity of preferred tech #2 highly dependent on…	XX XX XX XX XX
75	a d e f g	3 4 7 9	XX XX XX XX	Reduction in 75M/yr budget by 20% would result in...	XX XX XX XX XX

Overview: Study Goal

- **What is the best technology investment portfolio that enables a Mars exploration program that is resilient?**
- **Integrate three different sources of important information:**
  - Program science return is evaluated based on a number of high priority MEPAG-defined measurements grouped into Pathways (McCleese/ Arvidson)
    - One measure of resiliency is the ability to be responsive to multiple possible futures (pathways) weighted according to Program policy
  - This analysis considered the 12 missions identified by the study leads under the direction of F. Jordan, plus 5 Scout classes identified by Steve Matousek.
    - The missions studied span the space of the various desired measurements
    - The missions identified the enabling capabilities/technologies
  - The technology metric, current state, performance forecast and funding requirements to achieve TRL-6 came from Samad Hayati.

Approach

Define Mars Goals In terms of MEPAG measurements and Pathways

Postulate missions to achieve these measurements

Identify capabilities and technologies required for desired missions

Define technology metrics,costs, and likelihoods

Sample from technologies; compare to mission requirements

If any required technology for a mission is not feasible, mission utility is set to 0

Apply utility weighting (based on measurements performed and pathway)

Rank missions weighted by pathway and technical feasibility

Pick a budget available for disbursement

Create table of recommended technology investments

Analyze various assumptions in sensitivity analysis

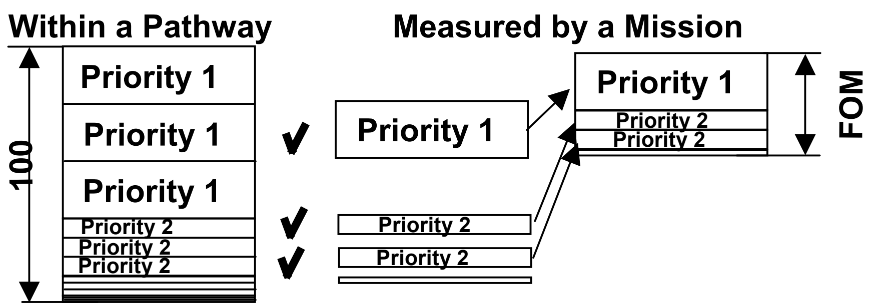
Prepare Results

Science Goals and Objectives

1	**Determine if Life Ever Arose on Mars** ➢ Determine if Life Exits Today ➢ Assess the Extent of Prebiotic Chemical Evolution
2	**Determine the Evolution of the Surface and Interior of Mars (ÒGeologyÓ)** ➢ Determine the nature and sequence of the various geological processes (volcanism, impact, sedimentation, alteration, etc.) that have created and modified the Martian crust and surface. ➢ Characterize the Structure, Composition, Dynamics and History of the Interior.
3	**Determine the Climate History for Mars** ➢ Characterize the Present Climate and Climate Processes ➢ Characterize the Ancient Climate and Climate Processes
4	**Prepare for Human Exploration** ➢ Acquire Martian Environmental Data Sets ➢ Conduct In-Situ Engineering Science Demonstrations ➢ Emplace Infrastructure for (Future) Missions

Figures of Merit

MEPAG Measurments



$$\text{Figure of Merit for a Mission within Pathway} = \frac{\text{Number of Equivalent Priority 1 Measurements for Mission within a Pathway}}{\text{Total Number of Equivalent Priority 1 Measurements within a Pathway}}$$

$$\text{Figure of Merit for a Mission within Pathway} = \frac{\displaystyle\sum_{\substack{\text{Measurements}\\ \text{within Mission}\\ \text{within Pathway}}} \frac{\text{(measurement completeness factor)}}{DF^{\text{(measurement priority -1)}}}}{\displaystyle\sum_{\substack{\text{All Measurements}\\ \text{within Pathway}}} \frac{1}{DF^{\text{(measurement priority -1)}}}}$$

* (measurement completeness) changes between 0 and 1

$$\text{Figure of Merit for a Mission Within Pathway mixture} = \sum_{\text{All Pathways}} \text{Pathway Weight} * \text{Figure of Merit for a Mission within Pathway}$$

Mission / Measurement Relationships

	Overall FOM	Number of Measurements with a Given Priority				
		1	2	3	4	5
Scouts	10	4	4	3	3	1
MSL	21	5	9	1	0	10
Volcanology Rover	4	3	0	0	4	1
Magnetometer Gravity Mission	5	2	1	2	0	0
SAR	.02	0	0	0	0	1
Atmospheric Mission Orbiter	12	4	5	1	8	3
Surface Science Orbiter	9	1	1	1	6	2
Polar Layer Deposit Rover	12	7	3	1	4	1
MSR	20	4	7	2	3	2
Wildcat	8	1	3	2	3	3
Sabertooth	8	2	4	4	2	5

* FOM ⇒ 60% In-Situ, 20% Global Cycle, 20% MSR

Priority "n" measurement is 3 times more valuable than priority "n+1"
All measurements performed constitute FOM=100. For measurements beyond MSL, apply unity weight to categories of assigned (C), Primary (C1), and assigned secondary (C2) measurements, apply 0.5 to auxiliary measurements (d).
For MSL, apply unity to assigned primary (C), apply 0.5 to TBD, apply 0.5 to partial measurements.

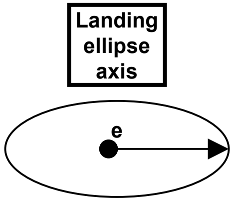
Technology Path Network

	Precision Landing, Kilometers	Impact Attenuation Landing Survivability, m	Hazard Avoidance, meters	On-orbit Science, meters/ pixels	Forward Planetary Protection, No. org.	Sample Char. TRL	Sub Surface Access, meters	Mobility, Meters/Sol	Sample Handling, ppm	Back Planetary Protection, microns	Telecom Network Data Rate, Megabits/sec	Mars Orbit Rend. Capture Δv, meters/sec	Long-Term Survivability	Scout Specific Technology
Volcanology Rover	1	2	⊘	⊘	5	6	⊘	8	⊘	⊘	11	⊘	13	⊘
MSL	1	2	3	⊘	5	6	7a	8	9	⊘	11	⊘	13	⊘
Magnetometer/Gravity Orbiter	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	11	⊘	31	⊘
SAR Orbiter	⊘	⊘	⊘	4	⊘	⊘	⊘	⊘	⊘	⊘	11	⊘	31	⊘
Imaging/Atmospheric Orbiter	⊘	⊘	⊘	4	⊘	⊘	⊘	⊘	⊘	⊘	11	⊘	31	⊘
Surface Science Orbiter	⊘	⊘	⊘	4	⊘	⊘	⊘	⊘	⊘	⊘	11	⊘	31	⊘
Polar Layer Deposit Rover	1	2	⊘	⊘	5	6	⊘	8	9	⊘	11	⊘	13	⊘
Mars Sample Return	1	2	3	⊘	5	6	7a	8	9	10	11	12	13	⊘
Wildcat	1	2	3	⊘	5	6	7b	⊘	9	⊘	11	⊘	13	⊘
Sabertooth	1	2	3	⊘	5	6	7c	⊘	9	⊘	11	⊘	13	⊘
Scout_1	1	2	3	⊘	5	6	⊘	8	⊘	⊘	11	⊘	13	14

$\boxed{N}$ **= data reference code**

⊘ **= technology not required**

Data Sheet for Precision Landing



Attribute Definition: Semi-major axis of landing ellipse in kilometers

1. Estimate length of semi-major axis for this technology assuming task succeeds with probability 100%; (pick one)

Point estimate (best guess) ________ **or** Range estimate (low to high) 5-10 km **or** Estimate e

e	P(x<e)
___	0
___	.25
___	.50
___	.75
___	1.00

2. Enter your estimate of actual probability of success that technology will be developed (0-100%).

85%

3. If the technology task fails, what is the best state-of-the-art likely to be achieved? (default—use current SOA)

100km

4. Estimate the budget profile in 3 year blocks (2002 M$)

3	6	9	12
10	0	0	0

5. Enter total technology development cost for this technology (2002 dollars)

Point estimate (best guess): $ M **or** Range estimate (low to high): ____ - ____ $M

Notes, Assumptions:

$4M optical nav, $4M G&C $2M continuing to get TRL-6 in 05 (PDR) for MSL 09 launch; as soon as subsonic chute deployed, task is done. Could be continued if any post-MSL missions identify a need for tighter landing accuracy.

[Optional] This technology applies to following mission(s) (check all that apply if known, otherwise leave blank):

- ☒ VOL
- ☐ ROV
- ☐ RVL
- ☐ MAG
- ☐ SAR
- ☐ IMA
- ☐ SSC
- ☒ POL
- ☒ MSR
- ☒ WLD
- ☒ SAB
- ☒ SCT_1

We Do Have This Table!

Annual Technology Investment ($M/yr)	Preferred Technology	Missions Enabled	MEPAG Meas. Enabled Priority	MEPAG Meas. Enabled Number	Comments	Sensitivity Analysis)
25 Cost Profile (2002 $M): [13, 13, 13, 8.4, 8.4, 8.4, 0, 0, 0, 0, 0, 0]	o On-orbit science o Telecom network, navigation o Multimission survivability orb.	o MAG orbiter o SAR orbiter o Imag/Atmos orbiter o Surface Sci. orbiter	1 2 3 4 5	7 6 3 8 9	15 out of 2047 portfolios meet this budget constraint. Other mission portfolios eliminated by larger number of required technologies, hence larger investment costs that violate budget.	XX XX
			FOM = 14			

We Do Have This Table!

Annual Technology Investment ($M/yr)	Preferred Technology	Missions Enabled	MEPAG Meas. Enabled Priority	 Number	Comments	Sensitivity Analysis)
50a **{Min Cost}** Cost Profile (2002 $M): [45.5, 45.5, 45.5, 17.7, 17.7, 17.7, 16, 16, 16, 5, 5, 5]	o Precision landing o Impact attenuation o Hazard avoidance o Forward planetary protection o Sample characterization, surface o Sub-surface access, shallow o Mobility o Sample handling, contam. o Telecom network, navigation o Multimission survivability: lander o Scouts	o MSL o Scouts o POL	1 2 3 4 5 FOM = 30	17 23 8 15 11	225 out of 2047 portfolios meet budget constraint. Other mission portfolios driven by larger number of required technologies, hence larger investment costs; options with higher technology value and smaller budgets possible, but pathways influence eliminates. This option maximizes technology, but minimum cost criterion only allows 3 missions.	See 50b option for option to maximize number of missions.
50b **{Max missions}** Cost Profile (2002 $M): [46.5, 46.5, 46.5, 22.4, 22.4, 22.4, 20, 20, 20, 10, 10, 10]	o Precision landing o Impact attenuation o Hazard avoidance o Forward planetary protection o Sample characterization, surface o Sub-surface access, shallow o **<SUB-SURFACE ACCESS, 30M>** o **<SUB-SURFACE ACCESS, DEEP>** o Mobility o Sample handling, contam. o Telecom network, navigation o Multimission survivability: lander o **<MULTIMISSION SURVIVABILITY: ORB>** o Scouts	o MSL o Scouts o Volcanology o POL **PLUS** o **MAG orbiter** o **WLD** o **SAB**	1 2 3 4 5 FOM = 36	19 25 10 16 15	Same as 50a except 3 additional missions enabled because not minimizing costÑ only has to be less than 50M/yr cap MAG allowed in because it does not require on-orbit Science technology program and multimission survivability: orb low in cost.	XX XX

We Do Have This Table!

Annual Technology Investment ($M/yr)	Preferred Technology	Missions Enabled	MEPAG Meas. Enabled: Priority	MEPAG Meas. Enabled: Number	Comments	Sensitivity Analysis)
50c+ {MSR Lower Limit} Cost Profile (2002 $M): [52.2, 52.2, 52.2, 19.4, 19.4, 14, 14, 14, 3, 3, 3]	o Precision landing o Impact attenuation o Hazard avoidance o Forward planetary protection o Sample characterization, surface o Sub-surface access, shallow o Mobility o Sample handling, contam. o Back planetary protection o Telecom network, navigation o Mars Orbit Rendezvous o Multimission survivability: lander	o MSL o MSR o Volcanology o POL	1 2 3 4 5 FOM = 41	18 27 8 16 12	2047 portfolios meet this budget constraint. Slack in budget permits larger number of required technologies across missions; This case minimizes cost which excludes some missions.	XX XX
75b {Max Missions} Cost Profile (2002 $M): [65.2, 65.2, 65.2, 32.8, 32.8, 32.8, 20, 20, 20, 10, 10, 10]	o Precision landing o Impact attenuation o Hazard avoidance o On-orbit science o Forward planetary protection o Sample characterization, surface o Sub-surface access, shallow o Sub-surface access, 30m o Sub-surface access, deep o Mobility o Sample handling, contam. o Back planetary protection o Telecom network, navigation o Mars Orbit Rendezvous o Multimission survivability: lander o Multimission survivability: orb. o Scouts	o MSL o MSR o Volcanology o POL **PLUS** o **MAG orbiter** o **SAR orbiter** o **Imag/Atmos orbiter** o **Surface Sci orbiter** o **WLD** o **SAB** o **Scouts**	1 2 3 4 5 FOM = 61	27 36 12 25 20	This case maximizes number of missions enables allowing higher costs. **Basic message: problem is unconstrained by this budget for the input costs.**	XX XX XX XX XX

Conclusions

- **We have developed and demonstrated a method for allocation of technology investment which maximizes science return in a budget-constrained environment**
  - The method synergistically includes Mars goals, pathways, measurements, missions, capabilities, technologies, costs, etc.
  - The method builds on the Pathways work of McCleese/Arvidson, the mission studies of Jordan, and the technology R&D program of Hayati
  - Early results seem plausible and interesting!

Recommendations for Further Activity

- Review the data inputs carefully and perform sensitivity analyses where appropriate
- Enter data for five separate Scout mission classes (rovers, landers, orbiters, aerials, networks)
- Develop data for graceful degradation when specified metric ranges are not achieved.
- Complement existing study with more intense focus on risk assessment and answering specific decision-related issues.